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Integrating electrostatic adhesion to composite structures

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ABSTRACT

Additional functionality within load bearing components holds potential for adding value to a structure, design or product. We consider the adaptation of an established technology, electrostatic adhesion or electroadhesion, for application in glass fibre reinforced polymer (GFRP) composite materials. Electroadhesion uses high potential difference (~2-3 kV) between co-planar electrodes to generate temporary holding forces to both electrically conductive and non-conductive contact surfaces. Using a combination of established fabrication techniques, electroadhesive elements are co-cured within a composite host structure during manufacture. This provides an almost symbiotic relationship between the electroadhesive and the composite structure, with the electroadhesive providing an additional functionality, whilst the epoxy matrix material of the composite acts as a dielectric for the high voltage electrodes of the device. Silicone rubber coated devices have been shown to offer high shear load (85kPa) capability for GFRP components held together using this technique. Through careful control of the connection interface, we consider the incorporation of these devices within complete composite structures for additional functionality. The ability to vary the internal connectivity of structural elements could allow for incremental changes in connectivity between discrete sub-structures, potentially introducing variable stiffness to the global structure.

Keywords: Multi-functionality, Composite, Electroadhesion

1. INTRODUCTION

Composites materials such as glass and carbon fibre reinforced polymers (GFRP and CFRP) have seen rapid increases in usage in recent years, and there is increased interest in providing multi-functionality to such materials/structures[1]. Controllable adhesion between sub-elements could add significant value to composite structures. The ability to vary the internal connectivity of structural elements would increase structural functionality by allowing for controlled relative displacement between discrete sub-structures, potentially yielding variable stiffness. A means of controlled reversible connectivity of a composite laminate surface to a number of substrates is considered.

In this paper a study is made of the use of electrostatic adhesion (or electroadhesion) for a controlled displacement or latching between composite structures. Since the work of Prahlad *et al* (2008) there has been growing interest in the use of electroadhesion for wall climbing robotics, and the aim is to extend this existing research to wider applications[2]. A number of electroadhesive devices have been incorporated into composite structures, with the ability to increase the shear holding force by up to 85 kPa.

A review is undertaken of current electrostatic adhesion technology and a consideration of the potential applicability of such devices within composites. An outline is provided of a means of fabrication for incorporation of electroadhesives within basic composite structures. A series of testing and experimental data is presented. Finally, an assessment of the preliminary results and consideration of further research for progression to a wider application is considered.

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2. BACKGROUND

Electroadhesion or electrostatic-adhesion uses high strength electric fields generated by high potential difference imparted across closely spaced electrodes[3]. The basic configuration of such a device is shown in Fig. 1.

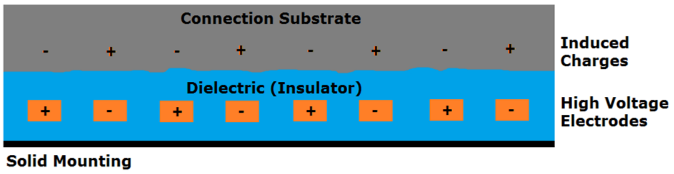


Figure 1: Basic configuration of an electroadhesive device

2.1 Existing electroadhesion literature

To date, the primary application of electroadhesives has been in the field of wall climbing robotics[2,4–6] and micro-grippers[7]. Herein the use of the technology for other applications is considered whereby integration of such devices into composite structures is a pre-requisite.

Electrostatic adhesion of structures is not a novel concept. Karagozler *et al*[8] have already considered electrostatic latching of separate modular structures. There has also been great interest in the use of electrostatic adhesion for structural stiffness control[9–13]. The primary difference between the research presented herein and the existing literature is the means by which the electrostatic holding force is implemented. All previous works mentioned consider using parallel plates either side of an interface, whereas electroadhesion exploits electrodes on only one surface, effectively making it applicable to a wider range of substrates. The primary reasoning for choosing electroadhesion over parallel plate designs was to remove any alignment issues inherent with this approach, and to extend the potential applications of this technology.

There is extensive research focusing on combining dry adhesive mechanisms with electroadhesive elements in order to maximise the achievable shear holding force/pressure, particularly for adhesion to rough substrates[14–16]. For some structural integration applications, it is desirable to have control over both surfaces of the attachment interface and, therefore, rough surface attachment may not be required.

2.2 Level of adhesive force

As Moore states "*Neither homogeneous dielectric materials nor homogeneous electric fields actually exist in nature, making it virtually impossible to calculate precise forces*", however, recent advances and research enable us to make reasonable estimates[17]. It is widely accepted that polarization of the connection substrate is the mechanism by which this form of electrostatic adhesion is able to attach to non-conductive substrates[7,18] and there is some agreement on a representative equation for estimated forces. For conductive substrates, electrons are free to move and this build-up of charge on the substrate is far simpler to envisage. In general, the following equation for the normal pressure generated by electroadhesion has been considered[6,14,15].

$$P_{normal} = \frac{\varepsilon_0 \varepsilon_r^2 U^2}{8d^2} \tag{1}$$

Where ε_0 represents the permittivity of free space, ε_r the relative permittivity of the dielectric layer, U the potential difference and d the dielectric thickness. Whilst only strictly applicable to conductive substrates, this has provided reasonable estimates of connection force to non-conductive substrates[6]. More recently, Mao *et al*. considered the effect of micron level air gaps that exist between two surfaces appearing to be in close contact, and derived the following[19].

$$F_{electrode} = \frac{\varepsilon_0 \varepsilon_{r1} \varepsilon_{r2}^2 U^2 S}{2(\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1)^2} \tag{2}$$

Here terms are as above, with the exception of subscript 1 representing the dielectric layer and subscript 2 represent the air gap. S represents the overall area of the electroadhesive so a total normal force of the electrode can predicted. This provides a greater understanding of the improved performance of electroadhesive devices on smooth substrates, and highlights the importance of intimate contact.

3. DESIGN AND FABRICATION

From Eq. 1 and Eq. 2, the factors beneficial in maximising the level of achievable holding strength of an electrostatic adhesive can be deduced as follows:

- Voltage (U), the maximum of which will be determined by the breakdown voltage of the dielectric. Ideally this should be maximised to maximise holding strength
- Dielectric thickness (d_1), the minimum of which will be determined by the breakdown voltage of the dielectric. Ideally this should be minimised.
- Air gap (d_2), the maximum is likely to be determined by the surface roughness of contact surfaces. Ideally this should be minimised.
- Relative dielectric permittivity (ε_{r1}) is more complicated as the optimum will depend on the air gap thickness and the dielectric thickness. With a dielectric thickness of 25 µm and using Eq. 2, for increasing air gap size the optimum relative dielectric permittivity reduces as in Fig. 2. This variable is likely to be limited by available materials, and will be a primary focus of optimisation once the surface roughness conditions are established

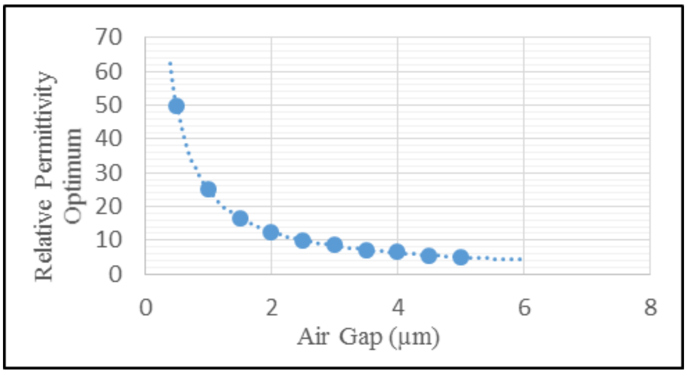


Figure 2: Estimated effect of air gap thickness between electroadhesive and attachment substrate on optimum relative permittivity to maximise holding force

With the need for controlled low thickness material with high dielectric strength and relative permittivity, Du Pont *Pyralux*, a laminate of 18 µm copper and 25 µm polyimide film offers great potential as a flexible printed circuit board (PCB) material. Electrodes can be produced with an attached dielectric layer in the form of the polyimide film[20]. *Labcenter Electronics Proteus 8 Professional* was used to create electrode designs from which etch resistant patterns could be transferred to the *Pyralux*. A chemical etching process (30 minutes in an etching tank of ferric chloride etching solution) was then used to create electrode patterns on polyimide backing (Fig. 3).

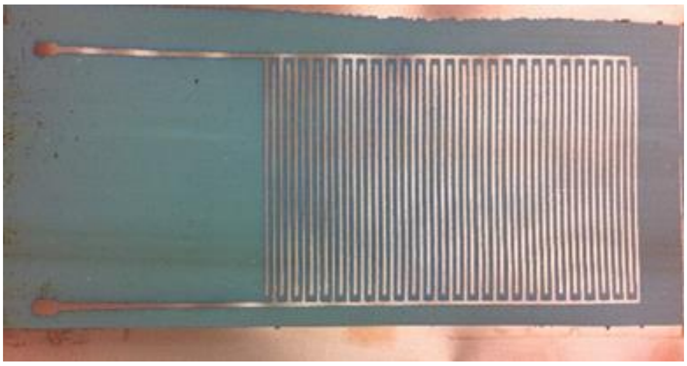


Figure 3: Etched interdigitated electrodes

Whilst the polyimide provides an insulated separation of the electrodes in one direction, it does not provide full enclosure. As a result, at high voltages, discharge can occur between the electrodes and severely limit the maximum potential difference that can be imparted, and thus limit achievable holding pressure/force. Integration into a FRP composite provides a novel solution to this limitation. Using a common practice of laminating of pre-impregnated plies of fibre/epoxy (Gurit Systems SE70 glass/epoxy) to manufacture the composites structure, the epoxy can function as a dielectric between adjacent electrodes, and thus fully insulate the electroadhesive. The etched *Pyralux* is included as an extra layer in the lamination process, and then co-cured with the composite material. During the cure cycle, with a dwell at 110°C for 50 minutes, the epoxy resin in the GFRP flows between the interdigitated electrodes and acts as a dielectric filler (Fig. 4).

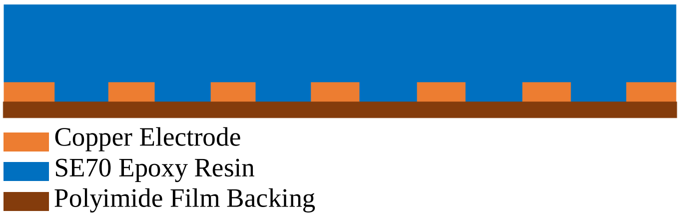


Figure 4: Integrated electroadhesive cross sectional diagram

3.1 Electrode configuration

In this study, the intention was to assess the feasibility of incorporating electroadhesive devices into a simple composite structure. As such, the electrode design was chosen from the literature without significant optimisation, and in future studies this will be addressed. For the general electrode design, a "comb configuration" of interdigitated electrodes was chosen (Fig. 3). Whilst concentric circular patterns have been shown to yield the highest average electric field strength across an electroadhesive device, there is only a reduction in field strength for comb configuration for a given smooth tile surface[3]. Comb configurations can be more easily integrated within rectilinear structures, maximising coverage area and thus holding pressure/force. Previous literature suggests that electrode gaps should be as small as possible, so practical distances of 1 mm and 0.5 mm electrode spacing were developed[18].Whilst the same study suggests varying electrode widths in order to maximise achievable average electric field strengths, for simplicity, and in line with an earlier study suggesting small widths improved holding pressure/force[20], consistent electrode widths of 0.5 mm were used.

3.2 Connection Substrates

In order to establish the level of achievable holding pressure/force for the integrated electroadhesive, a number of different attachment substrates were chosen. Four thin film materials were tested to observe the holding pressure for conformable substrates, each with different surface properties, both in terms of friction and relative permittivity (Table 1). GFRP samples with various surface coatings were also fabricated to observe the achievable holding pressure/force for less conformable substrates. The substrate coatings tests on GFRP include: 50 µm PVDF film (Du Pont *Tedlar*), 25 µm Polyimide and uncoated GFRP. In addition, two samples with a low abrasion high friction tape coating (Tesa 4563) were produced. The intention of such a coating was to improve the lateral holding strength for a given electrostatic normal force generated, and were produced for testing with polyimide dielectric films. All connection substrates were designed to have a contact area with the electroadhesive equivalent to 3850 mm^2.

Table 1: Flexible substrate thin film materials

Material	Relative Permittivity*	Friction Coefficient*	Examples of Similar
Polyimide	3.7	0.63	Yamamoto *et al*[4], Di Lillo *et al*[12]
Pyralux AC 182500R (Copper side)	N/A Conductive	1	Chen *et al*[21]
Pyralux AC 182500R (Polyimide side)	3.7	0.63	Chen *et al*[21]
Tedlar PVF TWH 20 BS3	11	0.18	Bergamini *et al*[10,22], Di Lillo *et al*[13]

**Expected from manufacturer data. Supplied here for reference only.*

3.3 Additional fabrication notes

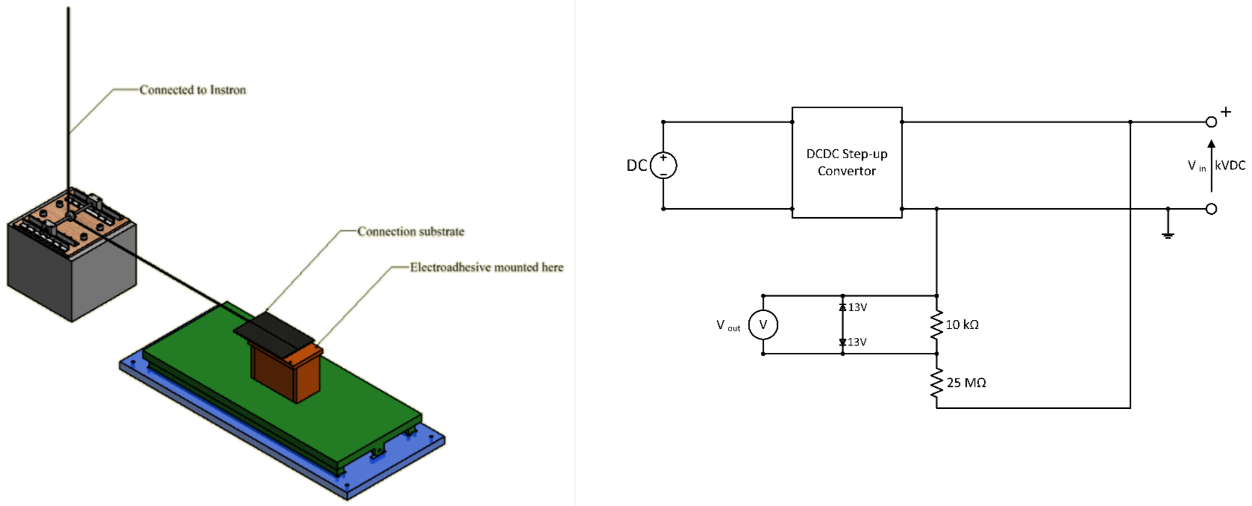
Whilst the polyimide was intended as the external dielectric coating, preliminary testing suggested that the achievable level of holding pressure/force might be very low. In order to provide a comparison to the literature, and extend the feasibility of the device, a co-cured electroadhesive was produced and then the polyimide was stripped and replaced with an Electrolube *DCA silicone conformal coating*, (Fig. 5). This provided a more conformable dielectric coating and helped improve the effective contact area for the electroadhesive device.

Figure 5: Silicone coated composite integrated electroadhesive

4. EXPERIMENTAL SET-UP

4.1 Mechanical rig

A selection of experiments were undertaken to establish the achievable level of shear force for the integrated electroadhesive devices. A shear force rig was created by modification of a tensile test rig. A stiff pulley system connected to an Instron 3343 tensile test machine with a 1 kN load cell enabled force to be transferred to connection substrates by means of a 3 mm diameter insulating wire (*Dyneema*) (Fig. 6 (a)).



(a) (b)

Figure 6: Experimental rig (a) Loading configuration (b) Basic electrical configuration

4.2 Electrical power system

To provide the high voltage necessary to energize the electroadhesive device, a commercially available low power DC-DC voltage converter (EMCO *F series*) was used. Fig. 6 (b) shows the basic arrangement, including a potential divider as a means to measure the output voltage generated. All high voltage devices were contained within an acrylic box to ensure the complete safety of the device at early design stages. The capacitance and current levels of the whole system need to be at safe levels for the applied voltage, and this would need careful consideration with respect to incorporation into a structure for a given application.

4.3 Test procedure

Initial testing was carried out to establish the level of achievable shear holding force from the composite integrated electroadhesive device. Before all tests, the electroadhesive and connection substrate surfaces were cleaned with acetone. This removes any surface residue and softens the silicone surface, both of which promote improved adhesion. For rigid substrates, a 1 kg mass was placed on top of the attachment substrate in order to ensure the substrates remained in intimate contact before initiation of the electroadhesive device. The mass also served to mitigate against edge peel of the connection substrate which would lead to premature failure. For the film substrates, a smaller mass of 100 g was required to hold the samples before voltage application. It is acknowledged that this resting mass could lead to an unfair comparison between the rigid and solid substrates, but for this study the main concern was the operability of the composite integrated electroadhesives, rather than detailed holding force considerations.

For all testing, a wait time of 100 seconds was taken before initiating the test. Based on time history data in a previous study, Chen *et al*[21],this was chosen as an appropriate wait time to ensure the electroadhesive had time to polarise the connection substrate. The rate of loading under displacement control was 10mm/minute. Instron *Bluehill* software was used to extract the load-extension response for each configuration. Each sample was tested 10 times at several specified voltages.

5. RESULTS

Results are provided obtained for achieved maximum shear stresses for rigid and flexible substrates with a variety of surface types. Due to the integration of the electroadhesive device into a composite material, the device itself is fairly rigid. Limitations in terms of achievable holding pressure/force resulting from this rigid GFRP backing are expected, which is a limitation requiring further mitigation. The initial results are for an integrated electroadhesive device with the DCA silicone dielectric.

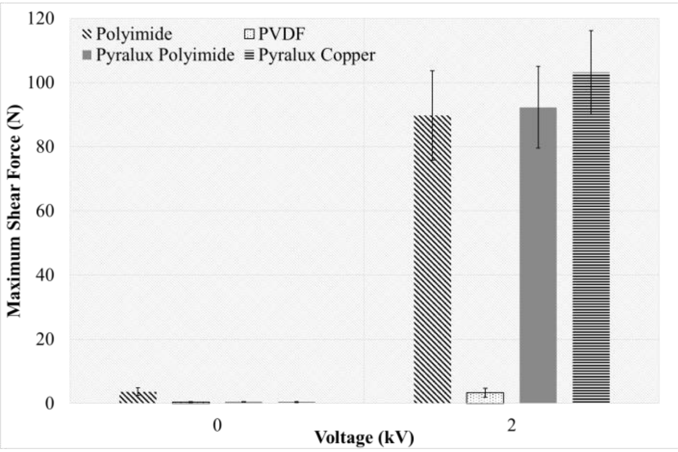


Figure 7: Maximum shear force (flexible substrates)

5.1 Flexible substrates

Whilst the electroadhesive itself is rigid, flexible connection substrates can conform to the surface topology of the device, potentially allowing for increased holding force. Table 1 shows the tested substrates with their key properties noted. From Fig. 7, the functionality of the integrated electroadhesive is apparent. At this stage voltages were limited to 2 kV to prevent dielectric breakdown and ensure the completion of all tests. The conductive surface of the *Pyralux* (copper face) yielded the highest shear force, attributable to the free movement of electrons, allowing for ease of charge build-up on the conductive substrate. The PVDF film did not achieve a significant increase in shear holding force, potentially due to the extremely low friction of the film.

5.2 Solid Substrates

Despite the expected limitations of rigid to rigid contact for electroadhesives, the solid substrates yielded promising results. This is attributable to the conformability of the silicone dielectric and is discussed later. From Fig. 8 it is clear that initiation of the 2 kV energising of the electroadhesive produced a substantial increase in shear holding force for all of the sample substrates tested.

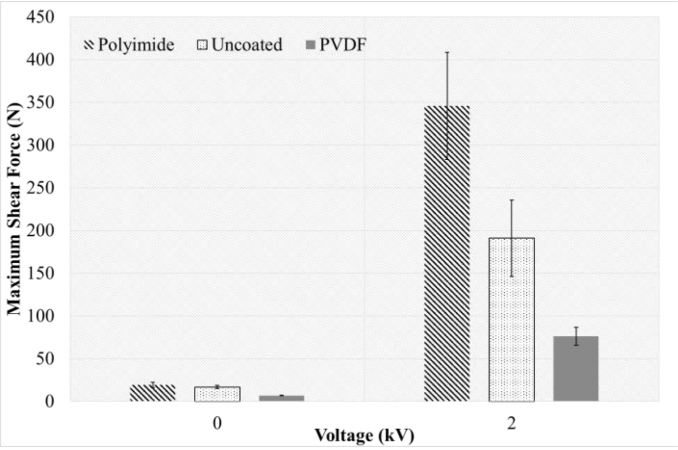


Figure 8: Maximum shear force (rigid substrates)

A comparison of the forces achieved after normalising for the observed friction at 0 kV shows the calculated normal adhesion at 2kV for the uncoated GFRP and the PVDF (*Tedlar*) coated GFRF yielded similar values at just over 110 N (Fig. 9). However, the Polyimide coated sample had a normalised value close to 180 N. This attributed to an improved surface finish compared to the inherent variability in the GFRP fabrication process, notwithstanding the conformability of the dielectric coating, which will be unable to completely overcome surface roughness effects, as observed by Ruffatto *et al*[23]. It is possible the PVDF did not yield high holding forces as expected due to its presence as a thin film. The work of Ruffatto *et al* noted the importance of the electric field strength at a depth of 3 mm, which suggests surface alterations in terms of permittivity would be less useful than those deeper in the connection substrate[23].

One would expect the flexible substrates to yield higher shear holding forces than the rigid substrates, however, this was not the case. Upon inspection of the failure mode of the samples, localised shearing and peeling of the flexible substrates led to propagation of separation from the electroadhesive elements and ultimately failure at the interface.

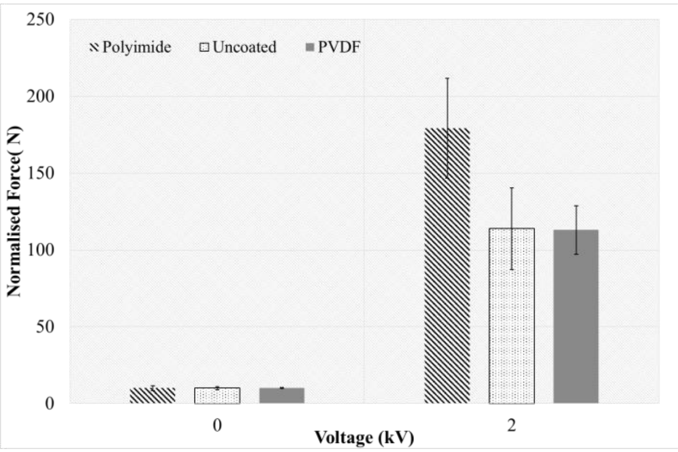


Figure 9: Friction normalised shear force (rigid substrates)

5.3 Polyimide dielectric

The original reasoning for the use of etched *Pyralux* was to enable a one-step fabrication process for the electrodes and dielectric coating. The etching process allowed for a rapid and repeatable means of electrode production, with flexibility to change electrode designs by simple artwork alterations at the etch resist stage of the process. The polyimide is provided as a ready attached dielectric coating of relatively consistent thickness. If the polyimide could function as an effective dielectric coating for the electroadhesive, the stripping and silicone coating becomes superfluous. However, the conformability of the softer silicone coating is probably the reason for significant improved holding forces, despite the rigid nature of the composite integrated electroadhesive device.

Table 2: Operation of integrated electroadhesive - polyimide dielectric (rigid substrates)

Connection substrate	**Average maximum shear force (N)**		**Percentage increase**
	0 kV	3 kV	
Uncoated GFRP	2.1	3.1	45.4 %
GFRP with Tesa Tape	59.2	115.3	94.9 %
CFRP with Tesa Tape	46.3	118.2	155.3 %
GFRP with PVDF coating	2.4	5.7	140.2 %
GFRP with Pyralux (Polyimide surface) coating	1.6	2.1	34.1 %

From Table 2 the functionality of the integrated electroadhesive device is evident, however, the achievable adhesion modulation is significantly lower. The lack of conformability of the dielectric surface, along with the combined surface roughness of both the connection substrate and the integrated electroadhesive is likely to lead to the existence of an air gap between the contact surfaces. From Eq. 2 the existence of an air gap can significantly limit the achievable holding force. For the Tesa Tape coated samples, an increase in the maximum achieved shear holding force is achieved by a large increase in mechanical friction force at the expense of the electrostatic force. Considering the operation of the integrated electroadhesive for flexible substrates, a further comparison can be drawn.

In a similar manner to the rigid substrates, the electroadhesion with the polyimide dielectric is significantly less pronounced than with the silicone dielectric (Fig. 10). It is clear that the conformability of the dielectric layer is of key importance for the successful operation of these integrated electroadhesive elements.

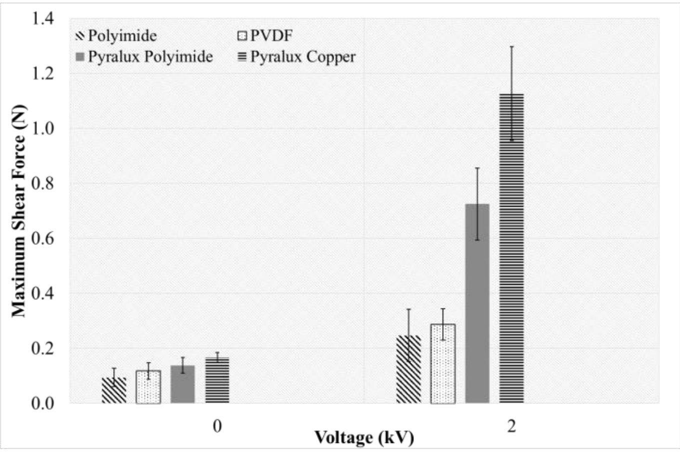


Figure 10: Maximum shear force - polyimide dielectric (flexible substrates)

5.4 Limitations

A key limitation to a composite integrated electroadhesive is its susceptibility to dielectric breakdown. When this occurs, a short circuit results between adjacent electrodes, preventing the generation of the strong electric field necessary to produce electrostatic adhesion. This failure has been observed for both the silicone dielectric and polyimide dielectric configurations (Fig. 11). This can be mitigated by ensuring the applied potential difference does not breach the dielectric strength of these layers. A further complication is that the composite manufacturing often results in minor voidage in the epoxy matrix (Fig. 12).

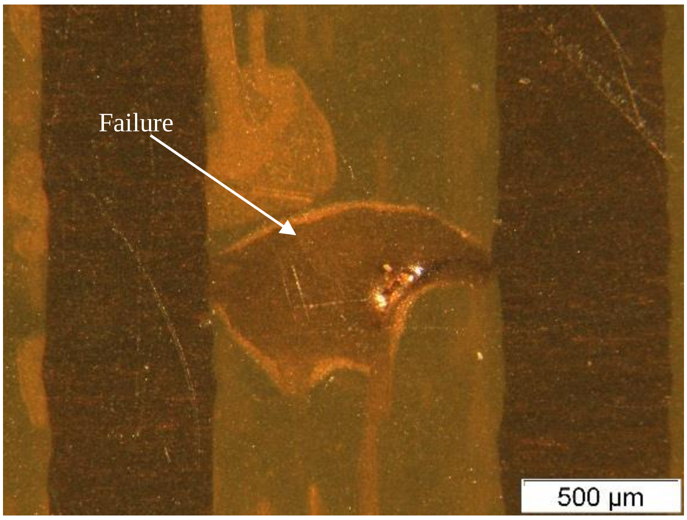


Figure 11: Dielectric breakdown failure

If this is present between electrodes, local discharge can occur, leading to device failure. Care is needed to ensure void free manufacture and apply a modular approach to the electroadhesive devices to ensure that local failure does not compromise the entire structure. The integration of the electroadhesive into FRP composites means the substrate is inherently rigid. This will be a limitation to the achievable holding force of the device. Modifications such as imparting conformability to the contact surfaces and improved dielectric properties can be employed to minimise any detrimental effects.

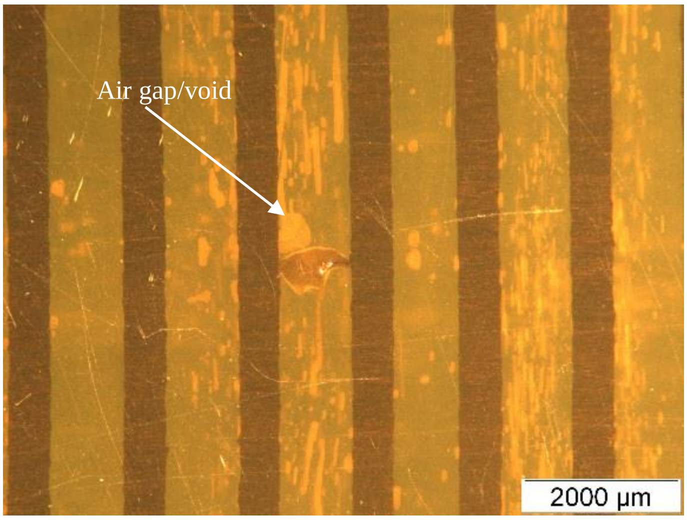


Figure 12: Voids/Air gaps in a composite integrated electroadhesive device

6. FURTHER WORK

Further research will consider possible applications and benefits for FRP integrated electroadhesive devices. For many applications an increase in the holding force will be required, and this will be a research goal. Improving the ability of the integrated device to tolerate small scale surface roughness will also be beneficial. Coatings with superior dielectric properties and conformability will offer significant benefits.

7. CONCLUSIONS

In this study, the successful fabrication of a functional electroadhesive device within a FRP composite laminate has been shown. A practical and effective manufacturing process has been developed which utilises established techniques from microelectronics and FRP fabrication. Choice of materials is key to achieving an optimal electroadhesive performance. Conformability of the dielectric material between the attached surfaces mitigates surface roughness of connected substrates, and maximises the holding force for both the flexible and rigid substrates tested. Maximum holding stresses of 90 kPa for a rigid substrate and 26 kPa for a flexible substrate have been achieved.

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